Fluvial architecture in actively deforming salt basins: Chinle Formation, Paradox Basin, Utah

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Abstract

Determining the response of fluvial systems to syn-sedimentary halokinesis is important for reconstructing the palaeogeography of salt basins, determining the history of salt movement and predicting development and architecture of sandstone bodies for subsurface fluid extraction. To assess both the influence of salt movement on fluvial system development and the use of lithostratigraphic correlation schemes in salt basins we have analysed the Triassic Chinle Formation in the Paradox Basin, Utah.

Results indicate that sandstone body development proximal to salt bodies should be considered at two scales: intra- (local) and inter- (regional) mini-basin scale. At the intra-mini basin or local scale, conformable packages up to 12 m of deep meandering fluvial channel deposits and associated overbank deposits are developed, which may thin, pinch-out or become truncated towards salt highs. When traced down the axis of a mini-basin, individual stories extend for a few hundred metres, and form part of amalgamated channel-belt packages up to 60 m thick that can be traced for at least 25 km parallel to palaeoflow. Where salt movement outpaces sediment accumulation, progressive low angle unconformities are developed along the flanks of salt highs. Significantly, in mini-basins with high sand supply, sandstone bodies are present across salt highs where they show increased amalgamation, decrease in thickness due to truncation and no change in internal sandstone body character.

At inter mini-basin or regional scale, spatial and temporal variations in accommodation space generated by differential salt movement strongly influence facies distributions and facies

correlation lengths. Broad lithostratigraphic packages (5 to 50 m thick) can be correlated within mini-basins, but correlation of these units between adjacent mini-basins is problematic. Knowledge of fluvial system development at a regional scale is critical as, fluvial sediment distribution is focussed by topography generated by growing salt bodies, such that adjacent mini-basins can have significant differences in sandstone body thickness, distribution and lateral extent.

The observations from the Chinle Formation indicate that lithostratigraphic-based correlation schemes can only be applied within mini-basins and cannot be used to correlate between adjacent mini-basins or across a salt mini-basin province. The key to predicting sandstone body development is an understanding of the timing of salt movement and reconstructing fluvial drainage system development.

1 Introduction

Syn-sedimentary halokenesis has the potential to reconfigure sediment routing systems within sedimentary basins and may influence whether fluvial systems by-pass or deposit within salt-controlled mini-basins (e.g. Banham & Mountney 2013a). In many cases the 3D geometry of the salt body and associated basins are difficult to determine and often change spatially and temporally within mini-basins (e.g. Barde et al. 2002a, b; Prochnow et al. 2006; Banham & Mountney 2014; Ribes et al 2015) such that developing predictive models for the distribution of fluvial deposits in salt mini-basins is difficult. It is important to do so however, as fluvial deposits form significant hydrocarbon reservoirs in salt mini-basins, and in many cases reservoir distribution and architecture is a key uncertainty (e.g. Smith et al., 1993; Barde et al., 2002a,b; Newell et al., 2012). The importance and range in type of salt-related depositional systems mean that whilst a number of predictive models for alluvial sediment distribution in salt-mini-basins have been developed (e.g. Matthews et al 2007; Banham and Mountney 2013a,b, 2014) they have yet to be tested rigorously.

The exceptional exposure of the fluvial deposits of the Upper Triassic Chinle Formation in the north eastern part of the Paradox Basin Utah (Fig. 1) means that they have been studied extensively, with particular reference to the influence of salt movement on sedimentation (Jones, 1959; Blakey and Gubitosa 1984; Hazel 1994; Prochnow et al. 2005, 2006; Matthews et al. 2004, 2007; Banbury 2005; Trudgill 2011). Despite this work a number of uncertainties remain with respect to the nature of the interaction between sedimentation and salt body movement. In particular, there is a lack of knowledge associated with the correlation and time equivalence of individual facies and facies belts within and between mini-basins. Previous studies have taken either a lithostratigraphic approach to examining alluvial architecture and correlating within and between mini-basins (e.g. Hazel, 1994; Matthews et al. 2004, 2007) or studied specific areas of individual mini-basins (Prochnow et al. 2005, 2006). We focus on the detailed alluvial architecture and correlation within and between mini-basins in the Chinle Formation and assess the influence of salt movement in controlling alluvial architecture. Our interpretations differ from previous workers in that we suggest that a lithostratigraphic approach to correlation within Chinle salt mini-basins cannot be supported and that the relationship between alluvial systems and salt movement is more complex than has been recognised previously. This has important implications for understanding controls on alluvial architecture in actively deforming basin fill successions and for subsurface correlation both within and between reservoir intervals in adjacent salt mini-basins.

Geological Background

The Paradox Basin covers an area of approximately 50,000 km^2 and is a located in southeast Utah and southwest Colorado (Hazel 1994; Barbeau 2003; Fig. 1). This asymmetric foreland basin formed during the Pennsylvanian to Permian by flexural loading of the Uncompahgre Uplift to the northeast (White and Jacobson 1983; Barbeau 2003; Trudgill 2011; Fig. 1). The Uncompahgre Uplift trends northwest-southeast, is adjacent to the deepest part of the Paradox Basin, and is believed to have been the main sediment source for the Pennsylvanian–Triassic sediments in the adjacent parts of the basin (Mack and Rasmussen 1984).

Salt structures are restricted to the north-eastern part of the basin (Fig. 1), trend northwest-southeast and show a wide range of styles from pillows to salt walls (Figs 2, 3; Doelling et al. 2002; Matthews et al. 2007; Trudgill 2011). Salt movement initiated shortly after deposition in the late Pennsylvanian coincident with inception of the Uncompahgre Uplift (Baars and Stevenson 1981; Doelling 1988). This resulted in the development of a series of northwest-southeast trending salt walls generated above northwest trending basement faults (Hazel 1994). Salt movement propagated progressively basinwards (to the southwest) through time due to sediment loading, resulting in the diachronous filling of mini-basins between salt walls with the main phase of movement occurring from the late Pennsylvanian through to the late Triassic (Doelling 1988; Trudgill et al. 2004; Banbury 2005; Paz 2006; Trudgill 2011). Numerous workers have examined the relationship between salt movement and sediment deposition recognising stratigraphic thinning, inter and intra-formational tilted unconformities and variations in stratigraphic architecture within the late Pennsylvanian to late Triassic succession including the Honaker Trail, Cutler, Moenkopi and Chinle formations (Shoemaker and Newman, 1959; Stewart et al., 1972; Blakey and Gubitosa, 1984; Hazel, 1994; Doelling and Ross, 1998; Doelling, 2001, 2002; Doelling et al., 2002; Matthews et al., 2004, 2007; Trudgill et al., 2004;Banbury 2005; Lawton and Buck, 2006; Trudgill 2011; Banham and Mountney 2013b, 2014; Venus et al. 2015; Fig. 2). However, only recently have a range of generic models for fluvial architecture in salt mini-basins been developed (Banham and Mountney 2013a) and the aim of this paper is to examine the Chinle Formation fluvial architecture within this context.

The Chinle Formation was deposited between latitudes 5-15°N in middle to late Triassic times (Blakey and Gubitosa 1983). The climate at the time of deposition varied from humid/sub-humid in the lower part of the Chinle to arid/semi-arid in the upper half of the section (Blakey and Gubitosa 1984; Hasiotis 2002; Prochnow et al. 2006). The Chinle Formation within the Moab region unconformably overlies the Moenkopi Formation and is overlain by the aeolian Wingate Sandstone.

Chinle Formation Stratigraphy in the north-eastern Paradox Basin

The regional lithostratigraphy of the Chinle Formation has been erected outside of the north-eastern part of the Paradox Basin (Stewart et al 1972; Blakey and Gubitosa 1983, 1984) and cannot be readily applied to the study area (Stewart et al 1972; Doelling 1985; Hazel 1994). A local lithostratigraphic terminology was established by Hazel (1991, 1994) for sections adjacent to the Kane Creek Anticline (KCA) and was extended by Matthews et al (2004, 2007) across the north-eastern part of the Paradox Basin (Fig. 4). Matthews et al (2007) recognised 5 lithostratigraphic units in ascending order, the lower Chinle, lower-slope, black-ledge, upper-slope, and Hite bed. Due to the significant facies variations that occur within the salt mini-basins we believe this lithostratigraphy cannot be applied to each mini-basin, consequently we have simplified the lithostratigraphy to recognise three informal lithostratigraphic units: the lower Chinle, main Chinle and Hite Sandstone Unit. The distribution of these units is shown in Figure 5. As both the lower Chinle and Hite Sandstone Unit (previously termed Hite Bed; Fig. 4) have been described in detail previously (Matthews et al 2004, 2007; Prochnow et al 2005, 2006) a brief outline is given for each unit below, together with the main Chinle unit that forms the main focus of this work.

Lower Chinle

The lower Chinle, also referred to as the Mottled Strata and/or White Grit (Stewart et al. 1972; Hazel 1994) comprises fine to coarse grained quartz-rich sediment. The unit ranges from 0 to a minimum of 50 m in thickness. It locally overlies the Moenkopi Formation with an angular unconformity adjacent to salt structures but away from salt structures particularly in the west of the study area it has a conformable contact. The lower Chinle where present in mini-basins is generally a few metres thick and is normally conformably overlain by main Chinle strata displaying a distinct change in colour and facies type. In the Big Bend area of the Courthouse Syncline and along the west side of the Moab Valley salt wall (MVSW) it has an angular unconformable relationship with the overlying main Chinle unit (Matthews et al. 2004, 2007). In the Big Bend area, the lower Chinle thickens locally to 50 m and is strongly bioturbated with well developed paleosols described in detail by Prochnow et al. (2006).

Main Chinle

Within the main Chinle we include the different lithostratigraphic units recognised by Hazel (1991, 1994) namely Kane Springs sand bodies one, two and three and the lower-slope, black-ledge and upper-slope units of Matthews et al (2004, 2007). The main Chinle unit ranges from 35 to 130 m across the study area with the thickest sections located adjacent to active salt structures (Fig. 5a). Fluvial channel sandstone bodies form prominent black-weathering ledges that occur within all mini-basins throughout the main Chinle and are not restricted to specific stratigraphic intervals.

Hite Sandstone Unit

The Hite Sandstone Unit is an aeolian and fluvially-reworked aeolian package which occurs beneath the Wingate Formation. Although the contact between the Hite Sandstone and Wingate sandstone is recognised regionally as an unconformity surface (Stewart et al. 1972; J-0 of Pipiringos and O'Sullivan 1978), an angular unconformity is only present adjacent to the Moab Valley and Kane Creek salt structures, elsewhere in the study area the contact appears conformable. The Hite Sandstone Unit ranges from 2 to 13 m in thickness and is present in all sections. It normally has a sharp contact (occasionally erosional) with the underlying main Chinle unit (Dubiel, 1987; Hazel 1991, 1994; Matthews et al. 2007).

Study area and Methodology

To analyse the large scale interaction of drainage patterns and sedimentation around several salt bodies, 27 graphic sedimentary logs (Figs. 1 and 2) were recorded across the salt mini-basin province, together with photopanels, correlation panels and measurements of sand body geometries. Salt wall development produced a series of mini-basins approximately 10 km in width (Fig. 2). The King's Bottom and Courthouse mini-basins are the main ones discussed here (Figs. 2, 3, 4). Note that the Courthouse Mini-basin includes the Big Bend Mini-basin of previous authors (e.g. Matthews etal. 2004, 2007, Prochnow et al. 2006; Banham and Mountney 2013b). The following sections summarise the different facies identified and their distribution throughout the area.

Facies Analysis

Aspects of the sedimentology and ichnology of the Chinle Formation in the study area have been described in detail previously by Blakey and Gubitosa (1983, 1984), Doelling (1985); Dubiel et al. (1991), Hazel, (1991, 1994), Hasiotis (2002), Prochnow et al. (2005, 2006) and Matthews et al. (2004, 2007). The following analysis is a summary of our observations and those of previous workers where appropriate. Three facies associations are identified based on lithology, sedimentary structures, geometry, and nature of bedding contacts. Facies association distribution and palaeocurrent data for the studied logs are shown in Figure 5, log location and thickness data are given in Table 1.

Channel-Fill Sandstone Facies Association

Description

This facies association comprises fine to medium sandstones, with coarse grained pebbly lags and mudstones that form up to 12 m thick channel-fill units (Figs. 6 and 7). The base of the units comprises intraclasts of mudstone, sandstone, woody debris and shell material. Channel-fill units are 10 to 12 m thick and comprise low angle dipping surfaces (4 to 11°) that bound 0.5 to 2 m thick packages of fine to medium grained sandstones. Sedimentary structures within the sandstones are dominated by horizontal to low angle planar stratification often with a primary current lineation with subordinate sets of trough cross-strata up to 50 cm thick (average 30 cm). Up to 10 m thick mudstone-dominated sets of inclined heterolithic strata (composed of alternating claystone, siltstone and fine sandstone beds up to 15 cm thick) occur either overlying or lateral to sandstone-dominated channel-fill units (Fig. 6A, B) and commonly display localized soft-sediment deformation (Fig. 8). Fine-grained sandstones with current ripples and climbing ripple sets occur near channel-fill margins or towards the top of channel-fill bodies. Parallel laminated mudstones up to 2 m thick may overlie heterolithic packages. Palaeocurrent data taken from trough cross-strata show a wide range of directions (Fig. 5).

Sandstones are preserved as either isolated, single-story bodies (50 to 500 m wide, 1 to 10 m deep) or amalgamated, multi-story, multilateral sheets (Fig. 6A,B). The latter are up to 60 m thick and can be traced for > 10000 m parallel to the axes of mini-basins.

Interpretation

This facies association represents the deposits of a sandy and mixed sandy heterolithic meandering fluvial system. The low angle dipping surfaces developed within the channel-fill sandstone bodies represent up to 12 m thick lateral accretion packages developed within actively migrating point bar deposits (Jordan & Pryor 1992). The intraclast lags are developed at the toe of lateral accretion sets and record erosion and reworking of overbank mudstones and lacustrine material. Mudstone-dominated heterolithic units represent deposition in an abandoned channel still open to flow, whilst parallel laminated mudstones developed above the heterolithic packages represent a clay plug developed in an abandoned, closed channel (Jordan & Pryor 1992). The wide range in palaeocurrent data support an interpretation as a series of stacked point bar deposits.

Floodplain Facies Association

The floodplain facies association comprises four facies: splay, shallow lacustrine, paleosol and bioturbated floodplain

Splay facies

Description

Sheet-like units of parallel laminated mudstones, siltstones and subordinate micaceous, fine-grained sandstones form this facies. Sandstones form 1 to 20 cm thick, sharp-based beds with planar parallel lamination and/or current ripples that may stack to form beds up to 70 cm thick (Fig. 6E). Fining upward fine sandstone to mudstone cycles 5 to 35 cm thick are often developed with occasional root traces and/or desiccation cracks on bed tops. Bioturbation is sporadic and when present includes horizontal burrows generated by beetles and soil-dwelling insects (Hasiotis, 2002).

Interpretation

The fine grained and parallel laminated nature of this facies indicates deposition from suspension in a low-energy environment. Parallel laminated and current-rippled sandstones record rapid sand deposition from high-velocity unidirectional flows and are interpreted as splays associated with overbank flooding from fluvial channels. Root traces and/or mud cracks indicate subaerial exposure and desiccation, with bioturbation indicating sporadic colonisation by beetles and insects.

Shallow lacustrine facies

Description

Finely parallel laminated mudstones and siltstones with occasional fine grained sandstones up to 5 m thick comprise this facies and are restricted largely to the Big Bend area and east of this region. Occasional thin (<20 cm) limestone beds are present. Bed tops may contain horizontal burrows attributable to insect larvae (Hasiotis, 2002) and occasional root traces. The facies passes gradationally, both vertically and laterally, into overbank mudstones.

Interpretation

The occurrence of insect-larvae burrows imply that the fine-grained, finely laminated deposits were deposited from suspension in shallow water in perennial lakes (e.g., Hasiotis, 2002). Root traces indicate lake margin plant development and/or periodic exposure. Fine grained sandstone beds represent distal overbank flood events. Limestone beds record periods with calcium carbonate precipitation during phases of low clastic input.

Paleosol facies

Description

This facies is developed mostly in mudstones and siltstones and occasionally on poorly sorted sandstones and gravels. It is 10 to 200 cm thick and characterized by abundant root traces with associated mottling, haloes and calcareous rhizocretions (Fig. 6D). Subordinate burrows also occur attributable to crayfish and soil-dwelling insects (Hasiotis, 2002). Sand-filled mud cracks and ferric concretions are present locally. Primary bedding is largely to completely destroyed by root traces. The intensity of bedding-fabric destruction, colour, and relative proportions of different pedogenic structures is variable (e.g., Prochnow et al., 2005, 2006).

Interpretation

Root traces and associated pedogenic structures indicate paleosol development. The occurrence of mud cracks suggests episodic drying and desiccation, with soil dwelling traces indicating moderate soil moisture content associated with a fluctuating water table (Dubiel et al., 1991).

Variations in the intensity of bedding-fabric destruction, colour, and relative proportions of different pedogenic structures between paleosols reflect differing degrees of development, related to the duration and/or palaeogeographic location of soil formation (e.g., Prochnow et al., 2005, 2006).

Bioturbated floodplain facies

Description

This facies is largely restricted to the lower Chinle in the Big Bend area. Bioturbation is developed in medium to very coarse-grained, channel-fill sandstones, mudstones and sheet sandstones of the fluvial channel and overbank facies associations. Burrowing is approximately perpendicular to primary bedding although the pervasive nature of burrows has resulted in partial or complete destruction of bedding (Fig. 6C). The dominant trace fossils are crayfish dwelling burrows (*Camborygma*; Hasiotis, 2002), which form subvertical tubes up to 25 cm in diameter and 2 m long. Subordinate root traces and pedogenic mottling are also present.

Interpretation

Crayfish dwelling burrows indicate deposition in poorly drained subaerial environments with a high (1 to 2 m below surface) and fluctuating water table (Hasiotis, 2002). Abundant crayfish occur in humid to hot, wet seasonal climates (Hasiotis, 2002). Bioturbation intensity reflects the rate of sedimentation with more intensely bioturbated packages accumulating more slowly. The facies is interpreted to represent floodplain and/or marginal-lacustrine environments.

Aeolian Sandstone Facies Association

Description

This facies association comprises well sorted, well-rounded, fine- to medium-grained sandstones that form laterally extensive (>1 km) sheet sandstones 0.5 to 5.5 m. Sandstone sheets are irregular to sharp based and comprise either fine horizontal laminae or high-angle trough and tabular cross-strata with alternating fine- to medium-grained sandstone laminae. Thin (<10 cm) mudstone and siltstone beds with sand-filled mud cracks and occasional root traces occur within the sheet sandstones. This facies association is restricted to the Hite Sandstone Unit at the top of the Chinle Formation.

Interpretation

Well sorted and well rounded sandstone grains forming high angle cross-strata with alternating grain sizes on foresets, represent grainfall and grainflow deposits of aeolian dunes, with horizontal wind-ripple laminae representing sand sheet deposits (Dubiel, 1987; Hazel 1991, 1994; Matthews et al. 2007). Mudstone and siltstone beds correspond to wet interdune deposits.

Thickness and Distribution of Stratigraphic Units

Analysis of thickness data and facies distributions from regional cross-sections and photopanels allows constraints to be placed on the timing of salt movement during Chinle deposition in the Paradox Basin (Figs. 5, 7-11). The lower Chinle and Hite Sandstone Unit are present in most sections. The lower Chinle is normally 1 to 5 m in thickness but is significantly thicker immediately adjacent to the MVSW and in the Big Bend area (section 19), where in the former the section is 15 m thick and in the latter >50 m thick (Prochnow et al. 2006). The Hite Sandstone Unit has a relatively uniform thickness ranging between 2 and 13 m with an average of 8 m.

The thickness of the Chinle Formation in areas where no subsurface salt movement took place during deposition e.g. west of the KCA (e.g. sections 1, 2 and 3 of Fig. 2), ranges between 94 and 110 m. On both flanks of the KCA significant thinning of strata occur (Fig. 5a). From the western flank, the section thins progressively eastwards from 100 to 60 m over a distance of 9.5 km (sections 4, 5 and 6; Fig. 5a). In the King's Bottom Mini-basin a decrease in thickness from 140 to 60 m occurs over a distance of 10 km from section 13 adjacent to the MVSW southwestwards to section 6, 500 m east of the anticlinal crest (sections 13, 22 and 7; Figs. 5a, 7).

There is a general increase in thickness from 62 to 86 m of the Chinle Formation westwards from the Uncompaghre Uplift (sections 18 to 21, Fig. 5a) with a marked, but localised thickness increase in the Big Bend area (section 19). The thickness increase in the Big Bend area occurs primarily within the lower Chinle and does not appear to be associated with a visible salt structure (e.g. Prochnow et al. 2006). It has been attributed to localised salt dissolution at depth (Matthews et al 2007; Trudgill et al. 2011) creating a smaller mini-basin within the larger Courthouse Mini-basin. In the Courthouse Mini-basin, the base of the Main Chinle is not seen, but interpretation of seismic reflection data suggest an increase in thickness towards the axis of the syncline and thinning onto the crest of the MVSW (Trudgill 2011; Fig. 5).

A cross-section taken close to the axis of the King's Bottom Syncline (KBS) is illustrated in Fig. 5b. All measured sections range between 78 and 106 m in thickness. Sections 8 and 10 are both located on the present day axis of the KCA and display thicknesses of 97 and 91 respectively. These values are similar to those from sections unaffected by salt movement in the western part of the study area (e.g. sections 1, 2, 3 and 9; Fig. 5), indicating that KCA related uplift did not affect these areas during Chinle Formation deposition.

The section constructed parallel to the MVSB running north from section 13S (Fig. 5c), shows a marked decrease in thickness from 140 to 38 m over 4.7 km (from section 13S to 26) with an increase to 62 m northwards to section 16 over a distance of 10.3 km. A marked decrease in thickness from 140 to 44 m over a distance of 250 m is present south of section 13S to section 25 where the upper part of the main Chinle is present.

Facies Association Distribution and Palaeocurrent Data

Facies association distribution and palaeocurrent data from the logged sections are shown in Figure 5. The lower Chinle comprises channel-fill deposits interbedded with extensively bioturbated floodplain deposits. Palaeocurrent data are sparse often due to modification of sedimentary structures by post-depositional bioturbation and soil development. Published data from the Big Bend area show an overall northwesterly transport direction (Prochnow et al 2006). Two sections (12 and 13) for the Kings Bottom Mini-basin indicate both southwesterly and northeasterly directed transport.

The main Chinle sections show a wide range of facies association distributions. In the cross-section of the Kings Bottom Mini-basin (Figs. 5a, 7), meandering channel sandstone bodies are well developed towards the crest of the KCA (sections 6, 7 and 22; Figs. 5a, 7, 8). Floodplain deposits increase towards the east of the mini-basin (section 13) where they predominate in the upper part of the section and define separate discrete channel sandstone bodies in the lower section. Despite a wide range in scatter and variability within and between individual sections, a general north to northeasterly transport direction can be determined for sections 6, 7 and 22 on the flank of the anticline. In contrast, the principal and consistent transport direction in the eastern flank of the mini-basin (section 13S) is towards the west/southwest. West of the KCA, palaeocurrent data show a wide distribution with no overall prevalent transport direction (Fig. 5a).

In the Courthouse Mini-basin east of the MVSW, floodplain deposits dominate the majority of the studied sections (Figs. 5A, 6 and 9). Channel-fill deposits occur in the lower part of the sections in the Big Bend area and form the main facies association west of Big Bend although only a partial section is preserved (section 27 on Fig. 5A). On either side of the Cache Valley Salt Wall (CVSW) occasional, isolated single storey channel-fill deposits are developed within thick floodplain sections (Figs. 6F and 9). Paleoflow indicators although sparse, suggest a general northeasterly flow direction in all sections east of the MVSW.

In the cross-section parallel to the KCA and KBS (Fig. 5b), channel-fill deposits dominate in all sections forming an amalgamated meander-belt deposit that can be traced for at least 25 km. Two 1.5 km long photopanels which illustrate the lateral extent of the amalgamated channel-belt are shown in Figure 10. Floodplain deposits are present in all sections, particularly towards the top immediately below the Hite Sandstone Unit, and may define discrete single storey channel bodies or bound laterally and vertically amalgamated sandstone bodies. Palaeocurrent data show a wide range. The southern section (section 9), located in an area unaffected by salt movement, shows a clear northeasterly trend from two sandstone bodies. Data for other individual sections show distinct differences between interbedded and overlying sandstone bodies with all directions except due south recorded (e.g. sections 10, 12, 23 and 24). Despite the wide scatter in direction, an overall northerly transport direction can be inferred for the majority of sections.

In the section parallel to the MVSW (Figs. 5c, 11), amalgamated channel-belt deposits form a prominent weathering package (Unit B in Fig. 11) that overlies and is overlain by a floodplain dominated units (Units A and C respectively). The amalgamated sandstone body can be traced between all five sections (Fig. 5c) and is thickest in section 13S and thins to both the south (section 25) and north (sections 15 and 26) before increasing in thickness towards section 16. Paleoflow is directed to the west in both sections 13 and 15 and shows a wide spread in section 16.

General observations from the studied sections indicate that amalgamated channel-belt deposits dominate in the Kings Bottom Mini-basin, such that the mini-basin is the primary focus for transport and deposition of fluvial systems during main Chinle deposition (Fig. 5). Outside of the Kings Bottom Mini-basin fluvial channel deposits are less amalgamated and largely comprise one to three storeys separated by discrete floodplain intervals (Fig. 9). A regional decrease in fluvial channel presence occurs towards the top of all sections with floodplain deposition predominating prior to deposition of the Hite Sandstone Unit. Paleocurrent data within the salt mini-basins suggest an overall north to northwesterly paleoflow albeit with significant variability, whereas outside the salt-affected area (west of the KCA), flow directions are highly variable. East of the MVSW although floodplain deposition dominates throughout most sections, scattered channel deposits do occur in the lower part of sections with flow towards the NW. A gradual increase in channel occurrence occurs towards the MVSW from east to west (Figs. 5A, 9).

Syn-sedimentary Salt Movement and Alluvial Architecture

Variations in thickness, stratigraphic architecture, channel-belt distribution and localised development of unconformities suggest that salt movement strongly influenced sedimentation in the Kings Bottom Mini-basin (Figs. 5, 7, 9 and 10). Outside of this mini-basin, evidence for salt-movement during Chinle deposition is limited. West of the KCA the influence of salt on stratigraphy is minimal, with no thickness changes, control on channel type, amalgamation or paleoflow direction (Fig. 5a). In the Courthouse Mini-basin local salt dissolution influenced Lower Chinle sedimentation in a small depression (4 x 3 km) in the Big Bend area (Prochnow et al 2006; Matthews et al. 2007), although interpretation of subsurface well log data suggests a possible extension of Lower Chinle deposits to the NW (Banbury 2005). Salt movement had a relatively minor influence on main Chinle deposition in this area as indicated by slight thickening (section 19; Fig. 5a). However, whilst exposed sections of the main Chinle in the Courthouse Mini-basin outside of the Big Bend area show no evidence for significant thickness variations, an increase in channel development west of the Big Bend area is recorded in section 27 (Fig. 5A). Although it is possible that salt movement influenced sediment deposition in the western part of the Courthouse Mini-basin towards the MVSW, as indicated by seismic reflection data (Trudgill 2011) and increased channel presence in partly exposed sections, lack of exposure and limited subsurface data preclude a clear understanding of this area. East of the Courthouse mini-basin it is clear that the CVSW had no influence on Chinle deposition with similar section thicknesses and stratigraphy developed on either side of the salt wall (Figs. 5A, 9).

The section parallel to the MVSW (Figs 5C, 11) illustrates clear thickness variations and stratigraphic control related to topography of the MVSW. This together with the section across the Kings Bottom Mini-basin (e.g. Figs. 5A, 7) indicates that a complex 3D topography developed across the mini-basin during main Chinle deposition. In contrast, the section parallel to the KBS close to the centre of the mini-basin shows little to no thickness variation and contains the thickest accumulation of amalgamated channel-belt deposits in the study area (Figs. 5B, 10). A detailed analysis of the relationship between alluvial architecture in the King's Bottom Mini-basin is given below.

Western flank of King's Bottom Mini-Basin

Along the western margin of the King's Bottom Mini-basin localised development of angular unconformities together with sandstone body truncation and pinch out across the KCA are inferred to be related salt movement (Figs. 7, 8). Figures 8A and B show the overall thinning of the main Chinle on to the crest of the KCA, with Figures 8C and D illustrating details of different stratigraphic units. Four stratigraphic units (numbered 1 to 4 in Figs. 7, 8B and 8D) and four erosion surfaces (labelled ES1 to ES4 in Figs.7, 8B and 8D) can be identified. ES1 represents the unconformity surface between the Chinle and the Moenkopi Formation and is overlain by the lower Chinle and Unit 1. Unit 1 can be traced across the KCA (Figs. 7. 8A,B), but shows a decrease in thickness from 24 to 10 m resulting from a combination of onlap onto the anticline crest, aggradation over the crest (and potential linkage with fluvial systems west of the KCA) and truncation beneath ES2 due to erosion following salt movement.

ES2 can be traced down-dip into an equivalent, expanded conformable succession. Unit 2 has a relatively uniform thickness ranging from 28 m on the eastern edge of the exposure to 23 m where approximately 5 m of stratigraphy have been removed beneath ES3/4 on the crest of the KCA. Unit 2 comprises a conformable section of channel-belt deposits that pass laterally from the syncline across the crest of the KCA. This reflects relatively constant aggradation across both the mini-basin and KCA during deposition of Unit 2 and which ceased due to uplift and truncation beneath ES3 related to salt movement. The top of unit 2 is truncated by ES3 in the centre of the exposure (Fig. 8B and C) and amalgamates laterally with ES4 to form a composite erosion surface towards the crest of the anticline. The Unit 3 channel sandstone package overlies ES3 and is truncated and eroded beneath ES4 before reaching the crest of the KCA (Fig. 8B and C). This suggests that prior to truncation, Unit 3 extended further westwards across the KCA but that the unit was eroded beneath ES4 due to uplift associated with salt movement. ES4 records the greatest amount of erosion within the main Chinle succession cutting down and removing approximately 10 m of Unit 3 stratigraphy and amalgamating with ES3 across the crest of the KCA. ES4 is overlain by unit 4 which comprises horizontally bedded floodplain mudstones and splay sandstones passing upwards conformably into the Hite Sandstone Unit and the overlying Wingate Sandstone. In contrast to the underlying units, Unit 4 deposition was relatively uniform across the KCA indicating that salt movement had ceased.

The erosion surfaces developed across the KCA can be traced from the crest of the anticline down-dip into the syncline where they bound conformable packages of channel sandstone bodies (Fig. 8). The down-dip extent of truncation decreases upwards through the stratigraphy, with the basal erosion surface (ES1) having the largest lateral extent and ES4 at the top of the last channel sandstone body, having the smallest lateral extent. In addition the amount of material eroded from each stratigraphic unit increases upwards between each erosion surface. The combination of a decrease in the lateral extent of erosion together with increased erosion across the crest of the KCA through time indicates that salt movement was focussed into an increasingly smaller area of the KCA. The progressive decrease in unit thickness between erosion surfaces indicates a relative increase in the frequency of salt movement between ES1 and ES4, assuming a constant sedimentation rate, which is reasonable given there is no obvious change in depositional style throughout the succession.

Eastern margin of King's Bottom Mini-basin

Along the eastern flank of the Kings Bottom Mini-basin, the north-south trending section running parallel to the MVSW also shows significant variations in sandstone body thickness (Figs. 5C and 11). North of logged section 13, the section can be split into 3 units: Unit A a lower floodplain dominated succession, Unit B the main amalgamated sandstone body and Unit C, an upper floodplain dominated succession. The base of Unit A is not exposed across the whole panel but the unit thins significantly to the north where it is truncated beneath Unit B (Fig. 11D). Internally Unit B shows a complex fluvial architecture with amalgamation and truncation of channel bodies (Fig. 11C) and thins progressively northwards from 65 to 17 m over 4.5 km between sections 13 and 26 (Fig. 5c). Unit C shows a similar decrease in thickness from 55 to 15 m between the same sections. Both Units B and C increase in thickness to 35 and 30 m respectively to the north between sections 26 and 15 (Fig. 5c).

The southeast section of the correlation panel (Fig 5c), between sections 13S and 25 shows a rapid decrease in section thickness. An angular unconformity is present between the lower and main

Chinle (described previously by Hazel 1994, and Matthews et al. 2007), and Units A and B thin rapidly to the south with only the upper part of B developed at the base of section 25. At the top of section 25 and elsewhere across the whole panel, Unit C passes conformably into the Hite Sandstone Unit, which in turn has a conformable contact with the overlying Wingate Sandstone.

It is clear that salt movement influenced channel sandstone development immediately adjacent to the MVSW. The development of a thick section of main Chinle sediments across the MVSW, together with westerly-directed palaeocurrents (Fig. 5C) indicate that a topographic low was present within the MVSW through which fluvial systems were routed, linking the Kings Bottom and Courthouse mini-basins. It is likely these fluvial systems then linked with the generally northerly flowing channel systems developed in the axis of the Kings Bottom Mini-basin (Fig. 5B).

As well as the presence of the topographic low in the MVSW, salt movement is also indicated by the development of angular unconformities between the lower and main Chinle between sections 13S and 25 and between sections 15 and 26 where Unit A is also missing beneath Unit B. This suggests that local movement of parts of the MVSW was sufficient to generate unconformities on the flanks of topographic highs, but that sedimentation was continuous in the topographic low between the salt wall highs. The absence of obvious angular unconformities coupled with the decrease in thickness of Units B and C onto MVSW highs suggests that salt movement was relatively slow but continuous throughout deposition of these units. The conformable nature of the Hite Sandstone Unit suggests that salt movement had ceased prior to deposition.

Summary of Alluvial Architecture and Salt Movement

Angular unconformities and thickness changes record salt movement across the KCA and within the MVSW. The main period of salt movement occurred immediately prior to and after deposition of the lower Chinle, with a gradual decrease in activity during deposition of the main Chinle and cessation by the time of Hite Sandstone Unit deposition. Salt movement beneath the KCA was pulsed and relatively rapid in contrast to the MVSW where movement was relatively slow but continuous.

At a regional, inter mini-basin scale, the main influence of salt movement on alluvial architecture was to focus fluvial systems through relative topographic lows developed adjacent to and across growing salt structures such as the MVSW and along mini-basin syncline axes (Courthouse and

King's Bottom mini-basins). The restriction of fluvial systems to these topographic lows led to the accumulation of thick, amalgamated multi-storey channel-belt sandstone bodies up to 60 m thick, up to 5 km wide (transverse to syncline axis) and a minimum of 25 km in length (parallel to the syncline axis) in the King's Bottom Mini-basin.

At a local, intra-basin scale, salt movement controlled the lateral extent and shape of sandstone bodies along the flanks of mini-basins. In particular, when sediment accumulation outpaced salt movement fluvial systems were able to onlap and aggrade over salt highs. In contrast, when salt movement outpaced sediment accumulation angular unconformities were developed across salt structures. Significantly, as sediment accumulation outpaced salt movement on both flanks of the King's Bottom Mini-basin, thick sandstone bodies (up to 30 m) are preserved on top of salt highs (e.g. Fig. 7). In addition these sandstone bodies tend to have less heterolithic and floodplain material due to reworking, in contrast to the more expanded sections in adjacent topographic lows where floodplain and heterolithic material has greater preservation potential (Fig. 7).

The Hite Sandstone Unit at the top of the Chinle is continuous across all mini-basins with a relatively constant thickness. This suggests that salt movement had effectively ceased by the end of Chinle deposition. A general decrease in channel-belt development occurs towards the top of the main Chile and into the Hite Sandstone Unit in all studied sections (Fig. 5), which studies of the regional sedimentology and paleosol development suggest can be ascribed to deposition under an increasingly arid climate (Blakey & Gubitosa, 1984; Dubiel 1987, 1994; Prochnow et al. 2006).

Discussion

Paleogeographic reconstructions

Using the studied sections and photopanels, a series of palaeogeographic maps have been constructed for 3 periods during main Chinle deposition in the study area (Fig. 12). The reconstructions are intended to represent general changes seen in the sections through the main Chinle and represent the early to mid main Chinle (Fig. 12a), late mid main Chinle (Fig. 12b) and late Chinle just below the Hite Sandstone Unit (Fig.12c). The reconstructions highlight that: 1) the KCA and MVSW were the only active salt structures during main Chinle deposition, 2) there is a general decrease in fluvial activity through time, 3) there is a general decrease in fluvial input from the east through time, 4) a progressive abandonment of the fluvial system that passed through the

MVSW occurs, and 5) amalgamated channel-belt deposition is focussed into the King's Bottom Mini-basin. In addition the variable influence of the KCA is shown with expansion of the amalgamated channel-belt westwards across the axis of the KCA to link periodically with fluvial systems in the non-salt affected part of the Chinle basin (Figs. 12a,b).

The sedimentological observation that there was little or no sediment input from an easterly source during Chinle deposition is important. Previous workers have suggested that the Uncompaghre Uplift, which formed the western part of the Ancestral Rocky Mountains, was the principal source area for Chinle rivers along the north eastern flank of the Chinle basin (e.g. Hazel 1994; Blakey 1997; Matthews et al. 2007; Dubiel and Hasiotis 2011). It is also clear from stratal relationships however, that the Uncompaghre Uplift had been onlapped and buried prior to and during Chinle deposition (e.g. Banbury 2006; Trudgill et al 2011). Consequently, to account for the presence of fluvial channel systems in the study area, it is likely they were derived from an area to the south and east of the present study area with sediment transport aided by focussing of drainage systems within salt valleys.

Fluvial Planform

Previous work on the Chinle Formation in the northeastern Paradox Basin has interpreted alternating braided and meandering channel deposits to be present across the area (Hazel 1994; Matthews et al. 2004, 2007; Prochnow et al. 2006). However, the distinction between braided and meandering planforms in these studies is based primarily on the recognition of either predominantly downstream accretion (braided) or lateral accretion (meandering). Building upon the observations of Jackson (1978), Bridge (1985) and Jordan and Prior (1992) it is now recognised that in both modern and ancient amalgamated sandy meander belts the dominant form of accretion is downstream (Shukla et al. 1999; Hartley et al. 2015). We suggest that all the fluvial deposits in the Chinle Formation were deposited by large (up to 12 m deep) meandering rivers and that the variation in grain size is related to whether actively migrating point bars are preserved (sandstone dominated) or abandoned channel-fill deposits are preserved (heterolithic lateral accretion packages). The rapid lateral and vertical transitions between sandstone and heterolithic packages together with the variability in palaeocurrent directions supports this (e.g. Figs. 5-8, 10). An important implication of this interpretation is that no significant regional climatic or tectonic controls on channel planform can be inferred.

Chinle Formation Lithostratigraphy and Systems Tracts

The palaeogeographic reconstructions presented here differ significantly from previous work on the Chinle Formation in the same area. Matthews et al (2004, 2007) essentially took a lithostratigraphic based sequence stratigraphic approach to correlation within the Chinle Formation. They suggested that three lithostratigraphic units, a lower mudstone unit termed the Lower Slope, a sandstone unit termed the Black Ledge and an upper mudstone unit termed the Upper Slope (see Fig. 4 for lithostratigraphic schemes) are present in each mini-basin and could be correlated throughout the study area. They suggested that each lithostratigraphic unit was generated by changes in accommodation related to tectonic activity, with mudstones deposited during periods of high accommodation and braided fluvial sandstones developed during periods of low accommodation.

Our field observations and correlation panels (Figs 5, 7, 8 and 11), suggest that distinct facies assemblages previously interpreted as lithostratigraphic units are restricted to specific mini-basins. The main amalgamated channel belt sandstone unit is restricted to the King's Bottom Mini-basin although it may extend eastwards into the Courthouse Mini-basin linking through the low in the MVSW. Due to a lack of exposure this cannot be constrained. The main channel-belt sandstone unit does amalgamate with sandstones to the west across the KCA (e.g. Fig. 7), in an area unaffected by salt movement. Discrete channel belts occur only in the lower part of the Courthouse Mini-basin at Big Bend and are absent east of the CVSW (Fig. 5A), whereas channel-belts are present throughout much of the main Chinle succession west of the KCA. The variability in channel-belt development indicates that a lithostratigraphic correlation scheme based on alternating sandstone and floodplain units cannot be supported in the study area. In addition these observations suggest there is no overall large-scale tectonic control on facies association development in the main Chinle, and that the principle control on sediment accumulation and sandstone distribution was syn-sedimentary salt movement.

Controls on Sandstone Body Distribution in Salt Provinces

The analysis of the Chinle Formation succession suggests that active salt basins influence fluvial systems at two different scales. At a regional scale i.e. the scale of the salt province, the key role that salt structures play is to focus fluvial drainage pathways (Fig. 13). The presence or absence of fluvial channel belts within mini-basins is controlled by salt highs deflecting drainage into mini-basins. At a local, mini-basin scale, the role of salt structures is to influence fluvial architecture with expanded sections in the centre of mini-basins and amalgamated and truncated sections developed onto and across salt highs. Lithostratigraphic packages within mini-basins can be correlated with reasonable accuracy parallel to the axis of mini-basins, however lithostratigraphic packages are more difficult to correlate up to and across salt highs due to tilting, truncation and amalgamation (Fig. 13). The correlation of lithostratigraphic packages at a regional scale is problematic due to inherent differences in the development of stratigraphic successions in adjacent salt-controlled basins related to focussing of fluvial drainage systems and variable subsidence rates.

Most reconstructions of fluvial systems within salt provinces restrict channel development to the centre of mini-basins (e.g. Banham and Mountney 2013a). The examples illustrated here show that this is not always the case, and that fluvial sandstone bodies can develop immediately adjacent to salt highs where they may occur within rim synclines (e.g. Banham and Mountney 2013b) or on top of salt highs (Fig. 13B). Both the MVSW and the KCA salt highs have amalgamated channel belt sandstones developed across the top of these structures (Figs. 7, 8, 11, 13B). Sandstone bodies present on the top of the KCA are related to the earlier parts of the stratigraphy (Units 1 and 2 of Fig. 8), when sediment accumulation outpaced uplift of the KCA. Sandstones present on the top of the MVSW occur within the central part of the main Chinle and onlap and cover the MVSW topographic high (Unit B in Fig. 11). The internal architecture of the sandstone bodies in both cases is complex and involves subtle truncation surfaces and amalgamation related to tilting due to salt movement. Importantly, in both examples, evidence for the development of extensive palaeosols or floodplain facies on salt highs as predicted in a number of mini-basin facies models (e.g. Matthews et al 2007; Banham & Mountney 2013a; Venus et al. 2015), is absent.

Work on the stratigraphic unit that underlies the Chinle Formation allows constraints to be placed on the influence of salt movement and sediment input pathways through time within the Paradox Basin area (Fig. 13). Banham & Mountney (2013b) in a study of the Moenkopi Formation, showed that fluvial channel belts were initially located east of the CVSW In the Fisher and Parriott mini-basins (Fig. 3), but that by the end of Moenkopi deposition these salt mini-basins had grounded and that fluvial deposition was focussed west of the CVSW in the Big Bend area (Fig. 13). Our work on the Chinle supports this and shows that fluvial systems became increasingly focussed into the more westerly mini-basins (western part of the Courthouse Mini-basin and the King's Bottom

Mini-basins), prior to cessation of salt movement during the latter stages of Chinle Formation deposition. Overall, therefore, there is a progressive westerly migration of the locus of movement and the associated focussing of fluvial drainage systems through time, such that understanding the timing of salt movement, grounding of mini-basins and their control on fluvial system location is crucial for predicting sandstone body distribution in actively deforming salt basins.

Conclusions

A study of the Chinle Formation has been undertaken in the northeast Paradox basin, Utah, in order to assess the influence of syn-sedimentary salt movement on the development and distribution of fluvial systems. This study is largely focussed on the main Chinle and Hite Sandstone Unit that overlie the lower Chinle succession. Three facies associations are recognised: fluvial channel, floodplain and aeolian. Fluvial channel and floodplain facies are strongly influenced by salt movement and dominate the main Chinle succession whereas the aeolian succession is present only within the uppermost part of the Chinle Formation in the Hite Sandstone Unit. This latter unit is present cross the region, indicating that salt movement had ceased.

Our work suggests that sandstone body development proximal to salt bodies should be considered at two scales: intra- (local) and inter- (regional) mini-basin scale. At an intra-basin scale, the distribution of fluvial channel belts in the main Chinle is controlled by syn-sedimentary salt topographywith conformable packages of up to 12 m deep meandering fluvial channel deposits and associated overbank deposits developed parallel to the axes of salt mini-basins. Towards salt highs, in mini-basins where salt movement outpaces sediment accumulation sandstone bodies may thin, pinch-out or become truncated beneath low angle angular unconformities. In mini-basins with high sand supply, up to 30 m thick amalgamated sandstone bodies occur across salt highs where they show a decrease in thickness relative to equivalent sandstone bodies in adjacent mini-basin due to truncation, no change in internal sandstone body character and an absence of interbedded floodplain packages. All of these characteristics contrast with published models that suggest that floodplain and paleosol deposits should dominate across these relatively high areas.,

At a regional scale, salt-induced topography focuses fluvial drainage system development to such an extent that adjacent mini-basins commonly show significant differences in stratigraphy, such that the lithostratigraphic and systems tract based approaches to correlation commonly used in the study area and in other continental salt basins may lead to the production of erroneous correlation schemes. In addition, in the study area the a progressive westerly migration of the locus of salt movement and diachronous shifting of fluvial drainage systems through time, indicates that understanding the timing of salt movement, grounding of mini-basins and their control on fluvial system location is crucial for predicting sandstone body distribution in actively deforming salt basins

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Figures

Fig. 1 Location map illustrating the position of the study area within the Salt Anticline Region of south-eastern Utah and western Colorado. Modified from Blakey & Gubitosa (1984), Doelling (1985) and Hazel (1994). Pink areas indicate breached salt wall structures; red lines indicate anticlines developed above subsurface salt structures.

Fig. 2 Major present-day structural features and outcrop of the Chinle Formation within the northern Paradox Basin, Utah (after Huntoon et al. 1982; Doelling, 2001; Matthews et al. 2007). Numbered stratigraphic sections shown in Figure 5 are labelled A-A', B-B' and C-C'. Dashed line indicates location of structural cross-section shown in Figure 3. KBMB – King's Bottom Mini-Basin, CMB – Courthouse Mini-Basin, PMB – Parriott Mini-Basin, FMB – Fisher Mini-Basin.

Fig. 3 Regional cross section across the northeastern Paradox Basin showing present-day stratal architecture across major salt structures (modified from Trudgill et al., 2004). The line of cross section is located as the dashed line in Figure 2.

Fig. 4 Stratigraphic chart showing nomenclature used in this study and comparison with previous work.

Fig. 5 Cross-sections showing facies association distribution and paleocurrent data from the studied sections in the Chinle Formation. Location of sections are shown in Figure 2. Locations noted* were measured using a laser range finder. The section shown in Fig. 5A is oriented orthogonal to salt structures, Fig 5B runs parallel to the axis of the King's Bottom Syncline and Fig. 5C runs immediately adjacent to the Moab Valley Salt Wall.

Fig. 6 Field photographs illustrating facies associations. A) and B) Main Chinle, channel-fill facies association from the axis of the Kane Creek Mini-basin (section 12) with interbedded sandstone and heterolithic lateral accretion sets. C) Lower Chinle crayfish burrows from the bioturbated floodplain facies, Big Bend area (section 19). D) Main Chinle, paleosols for the floodplain facies association, section 11. E) Main Chinle, typical floodplain facies association (section 17).

Fig. 7 Log correlation panel across the King's Bottom Mini-basin. For location of numbered sections see Fig. 2. Box indications area of photopanel shown in Fig 8A/B between sections 6 and 7. ES1 to ES4 refer to numbered erosion surfaces. Numbers indicate units referred to in text.

Fig. 8 Photopanels of sections in King's Bottom Mini-basin between sections 6 and 7 on Figure 5A. A) Uninterpreted B) Interpreted. Panel is 2 km in width and located on the west side of Kane Springs Creek, close to orthogonal to the axis of the KCA (the axis of which is located just to the western edge of the panel). Note the changes in dip, decrease in thickness and truncation of multistorey sandstone packages to west. White box outlines area shown in C and D. Numbers indicate units referred to in text (Unit 4 includes the Hite Sandstone Unit) and ES1 to ES4 refer to numbered erosion surfaces. Arrows with numbers in A show location of logged sections 6 and 7. C and D: Detail of area highlighted in box in 8B. SLA = slumped lateral accretion, LA = lateral accretion. Numbers correspond to depositional units (Unit 4 includes Hite Sandstone Unit) and ES refer to erosional surfaces 1 to 4. Horizontal arrow shows onlap location of channel package in Unit 1.

Fig. 9 Photopanels of sections east of the MVSW. A) Photograph of the area adjacent to where section 18 (Fig. 5a) was measured at the eastern end of the section. Note the dominance of floodplain deposits, thin, sheet-like splay sandstones and lack of well developed channel sandstone bodies. B) Section 19 (Fig. 5a), in the Big Bend area showing reasonably well developed single storey to amalgamated channel sandstone bodies separated by laterally extensive floodplain packages and developed above the angular unconformity with the Lower Chinle. C) Section 21 (Fig. 5a), immediately west of the CVSW, showing floodplain dominated sedimentation and no channel sandstone bodies. Black arrows mark the base of the main Chinle in all sections.

Fig. 10 Photopanels oriented parallel to the axis of KCA and KBS. A) Section taken from Jacobs ladder in the east to the Colorado River valley in the west, section is 1.6 km in length. Note the dominance of amalgamated sandstone bodies throughout the Chinle succession, clay-rich lateral accretion packages form the weathered out units. Note the difficulty in correlating individual sandstone bodies over distances greater than a few hundred metres. B) Section running east-west along Long Canyon for 1.5 km in length. Note the lateral extent of sandstone bodies with lateral pinch outs and amalgamation of different bodies. The downstream accreting bodies tend to be more sand prone and form prominent beds, lateral accretion dominated bodies tend to be slightly finer grained and are more strongly weathered. White arrows mark the base of the Chinle, the top is taken at the base of the blocky Wingate Sandstone unit.

Fig. 11 Uninterpreted (A) and interpreted (B) photopanel along the western edge of the MVSW. A, B and C refer to units discussed in the text. Note the thinning of the Chinle packages to the north. C – Detail of the amalgamated channel-belt package highlighted in B and D detail of the pinch out to the north, arrows mark base of Chinle. Numbers in B refer to measured sections.

Fig 12 Schematic palaeogeographic reconstructions illustrating 3 stages in the development of the main Chinle unit in the study area, A) early to mid main Chinle, B) late mid main Chinle and C) late Chinle just below the Hite Sandstone Unit. Pink – floodplain, light grey – amalgamated channel belts. Active (dark grey) and inactive (light grey) salt structures are shown. MVSW – Moab Valley Salt Wall, KCA – Kane Creek Anticline, KBMB – King's Bottom Mini-basin.

Fig. 13 A) Three dimensional block model looking west of the Salt Anticline area illustrating the development of fluvial sandstone bodies through the Triassic stratigraphy (Chinle and Moenkopi Formations), with details highlighting different stratal geometries developed adjacent to salt structures. LC – Lower Chinle mini-basin developed in the Big Bend area. KCA – Kane Creek Anticline, MVSW – Moab Valley Salt Wall, CVSW – Caste Valley Salt Wall. KBMB 0 King's Bottom Nini-basin, CMB – Courthouse Mini-basin. Monekopi Formation thickness, facies and stratal geometries are influenced by movement of the CVSW (Banham & Mountney 2013b) but the Chinle displays no changes in thickness. Note that not all channel belts were active at the same time.
B) Schematic cross-section across the King's Bottom Mini-basin highlighting the amalgamation of channel sandstone bodies across the crest of the anticline through truncation related to uplift of the KCA and thickening of floodplain intervals into the adjacent mini-basin. Note that through time the unconformities progressively decrease in lateral extent as salt movement became increasingly focussed towards the crest of the KCA.